Ruling out some predictions of deeply-bound light-heavy tetraquarks using lattice QCD

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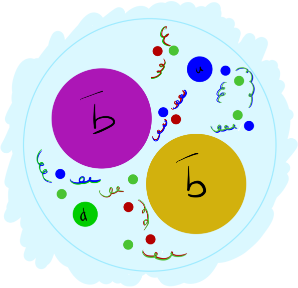
27 July 2021



Long wait for tetraquarks

SCHEMATIC MODEL OF BARYONS AND MESONS

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Received 4 January 1964

> The existence of tetraquarks (and other exotic states) has long been suspected!

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

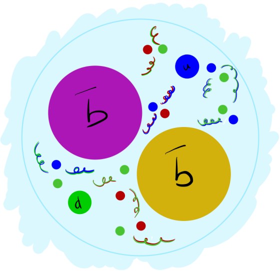
Diquarks

- ★ We are interested in:
  - ▶ light diquarks in a colour $\bar{3}_c$, flavour $\bar{3}_f$ and spin 0 configuration
    - ○ "good light diquark"
  - ▶ heavy diquarks in a colour 3_c, relative s-wave configuration

The term "good diquark" is of Jaffe's invention, for a nice review: [hep-ph/0409065]

A. Francis talk on "good" and "bad" diquarks @ 16:20 Wed, "QCD and hadron structure" session

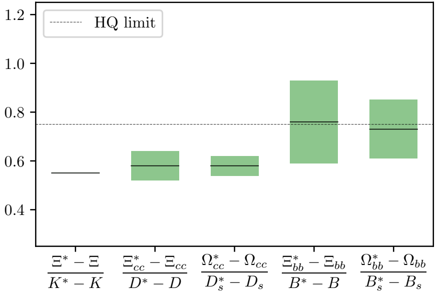
- ★ Degenerate heavy quarks: $J^P = 1^+$
- ★ Otherwise: we have access to $J^P = 0^+$ or $J^P = 1^+$
- ★ Light diquark $\implies$ $I = 0$ or $I = 1/2$

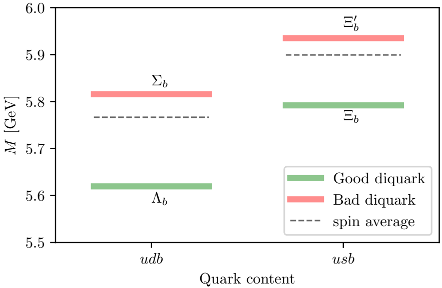


Information from baryons and mesons

- ★ Ordinary baryon and meson spectra can provide constraints for models
- ★ 3_c $\bar{Q}\bar{Q}$ serves as near-static colour source, like a single Q in a baryon (plus attractive colour Coulomb interaction)

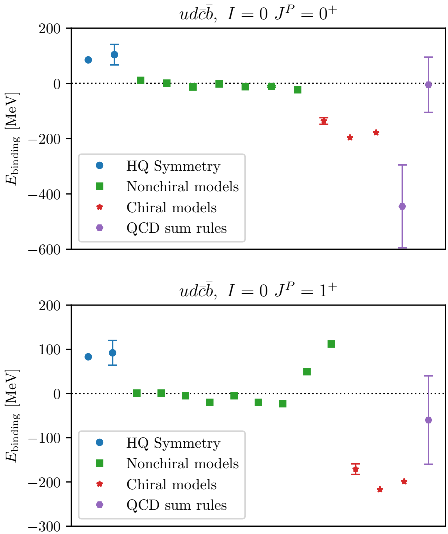
Numbers from PDG & [1409.0497]





- ★ Baryon spectrum suggests “good” light diquarks result in strong attraction.
- ★ Lighter quark mass $\rightarrow$ stronger attraction

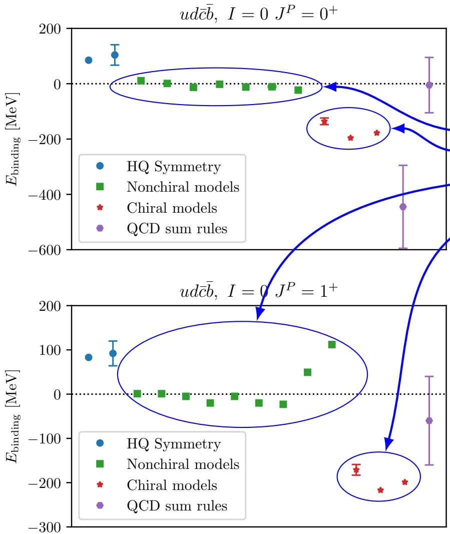
Example of model and other predictions



Examples of various $ud\bar{c}\bar{b}$ masses relative to the lowest two-meson threshold in the $I=0,\ J^P=0^+$ and $I=0,\ J^P=1^+$ channels.

We discuss model results completely for all channels in R.J. Hudspith, BC, A. Francis, R. Lewis and K. Maltman Phys. Rev. D 102, 114506 (2020), [2006.14294].

Example of model and other predictions



All fit to the ordinary meson/baryon spectrum; clear tetraquark difference

Examples of various $ud\bar{c}\bar{b}$ masses relative to the lowest two-meson threshold in the $I=0,\ J^P=0^+$ and $I=0,\ J^P=1^+$ channels.

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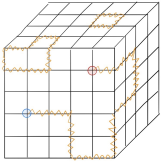
Some lattice details

Ensembles

$N_f = 2 + 1$ Wilson-clover ensembles – includes and extends PACS-CS ensembles

$L^3 \times T$	m_π [MeV]	$N_{\rm cnfg}$	a^{-1} [GeV]
$32^3 \times 64$	700	399	$2.194(10)$
	575	400	
	415	400	
	299	800	
	182*	121	
$48^3 \times 64$	192	122	
	165	88	



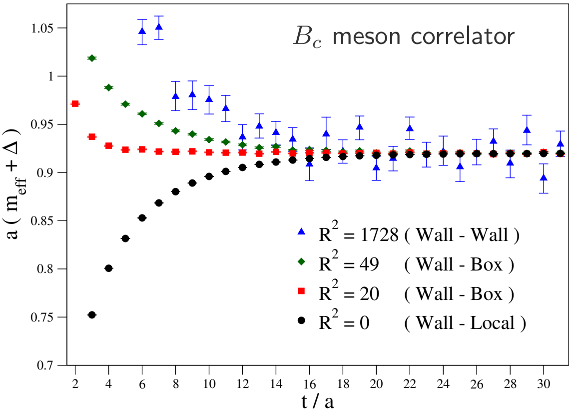
- ★ Coulomb gauge-fixed wall sources
- ★ c quarks: Relativistic Heavy Quark action
- ★ b quarks: Nonrelativistic QCD (NRQCD) action

Recent update: Box-Sinks

R. J. Hudspith, BC, A. Francis, R. Lewis, K. Maltman [2006.14294]

Improvement: box-sinks for better overlap with ground states.

$$S^B(x,t) = \frac{1}{N}\sum_{r^2 \leq R^2} S(x+r,t)$$



Tetraquarks on the Lattice

Fitting our tetraquarks

Construct correlators, $C_{\mathcal{O}_1\mathcal{O}_2}(t) = \sum_n \frac{\langle 0|\mathcal{O}_1|n\rangle\langle n|\mathcal{O}_2|0\rangle}{2E_n} e^{-E_n t}$ from:

$$
\begin{gathered}
D(\Gamma_1,\Gamma_2) = (\psi_a^T C\Gamma_1\phi_b)(\bar{\theta}_a C\Gamma_2\bar{\omega}_b^T),\\
E(\Gamma_1,\Gamma_2) = (\psi_a^T C\Gamma_1\phi_b)(\bar{\theta}_a C\Gamma_2\bar{\omega}_b^T - \bar{\theta}_b C\Gamma_2\bar{\omega}_a^T),\\
M(\Gamma_1,\Gamma_2) = (\bar{\theta}\Gamma_1\psi)(\bar{\omega}\Gamma_2\phi), \qquad N(\Gamma_1,\Gamma_2) = (\bar{\theta}\Gamma_1\phi)(\bar{\omega}\Gamma_2\psi),\\
O(\Gamma_1,\Gamma_2) = (\bar{\omega}\Gamma_1\psi)(\bar{\theta}\Gamma_2\phi), \qquad P(\Gamma_1,\Gamma_2) = (\bar{\omega}\Gamma_1\phi)(\bar{\theta}\Gamma_2\psi).
\end{gathered}
$$

We want to solve a GEVP to get energy levels, "principle correlators":

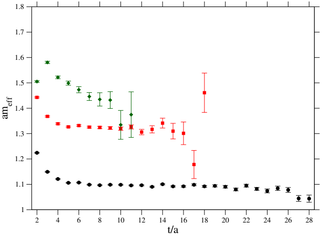
$$C_i(t) = \sum_{j,k} V_{ij}(\tau)^\dagger C_{jk}(t) V_{ki}(\tau)$$

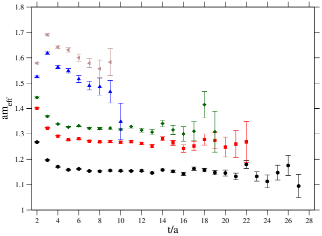
where V is made from columns of the eigenvector solution to:

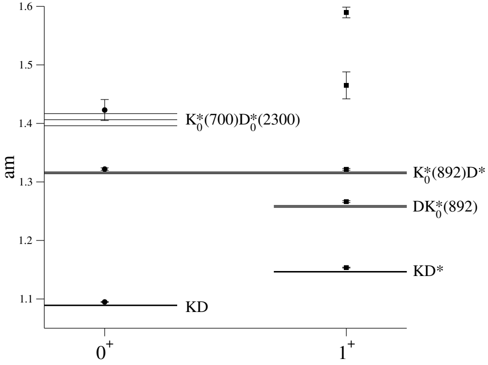
$$C_{ij}(t)v_j(t) = \lambda_i C_{ij}(t+t_0)v_j(t) \; .$$

$ud\bar{s}\bar{c}$ tetraquarks

R. J. Hudspith, BC, A. Francis, R. Lewis, K. Maltman [2006.14294]







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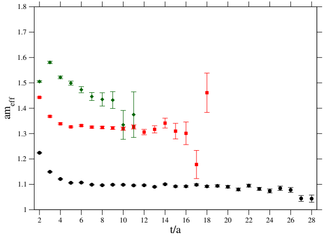

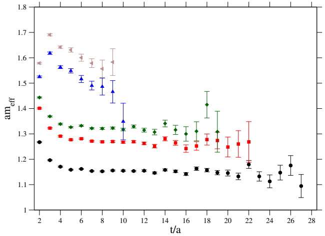

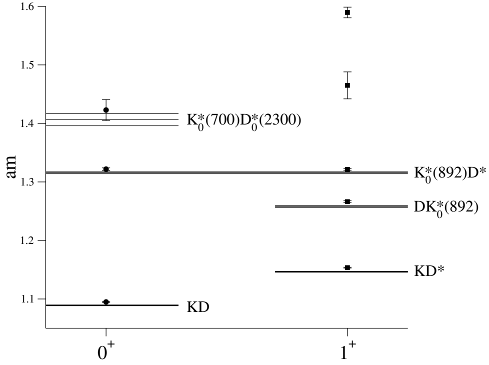

★ No evidence of deep binding in 0^+ or 1^+ channels

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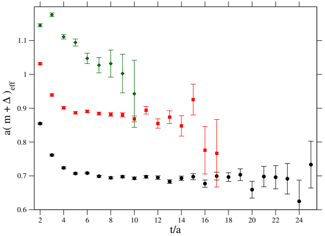

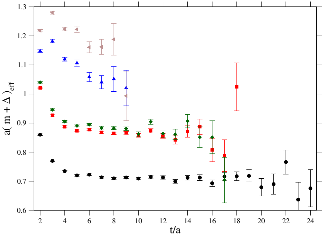

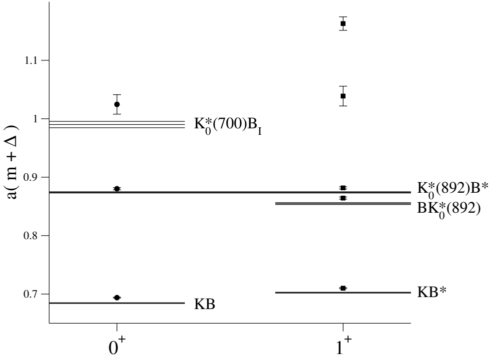

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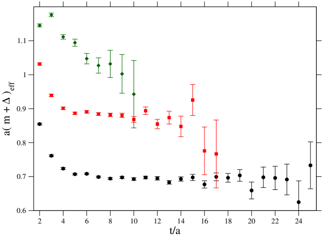

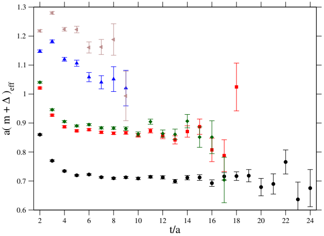

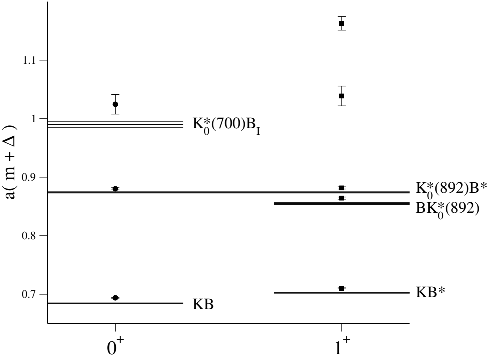

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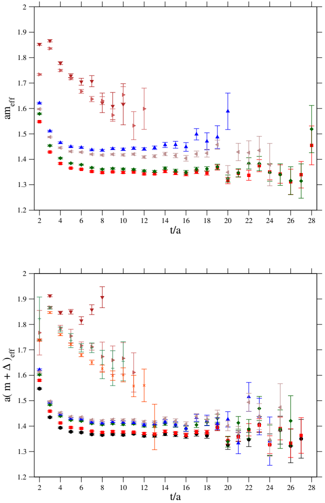

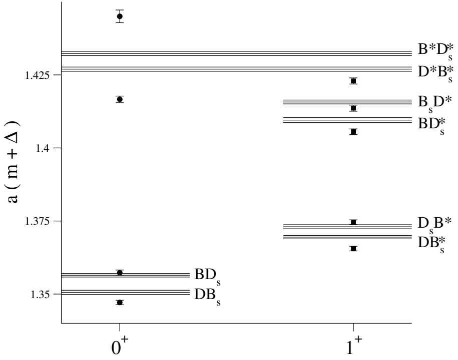

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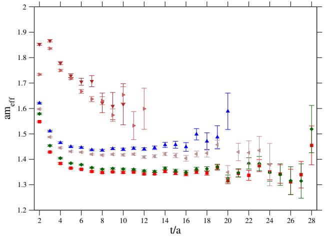

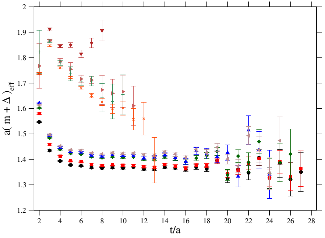

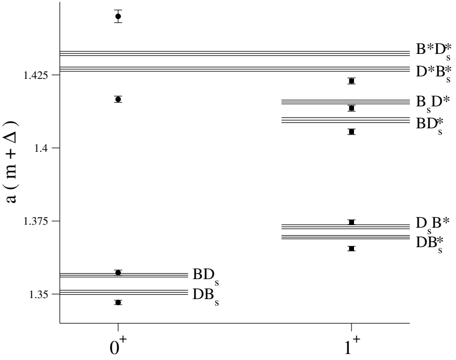

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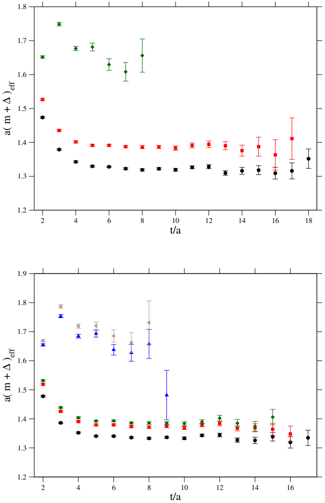

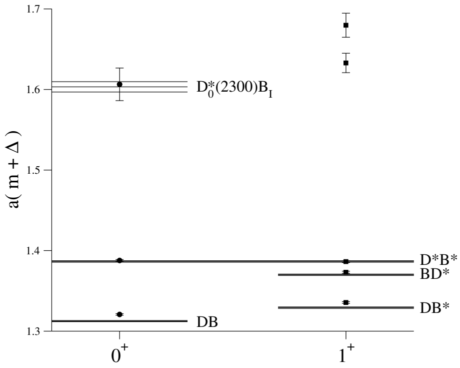

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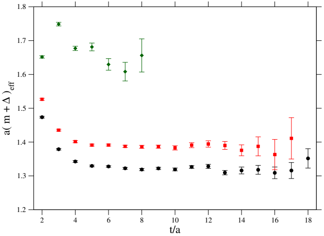

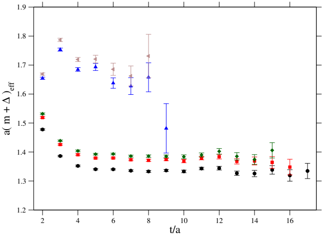

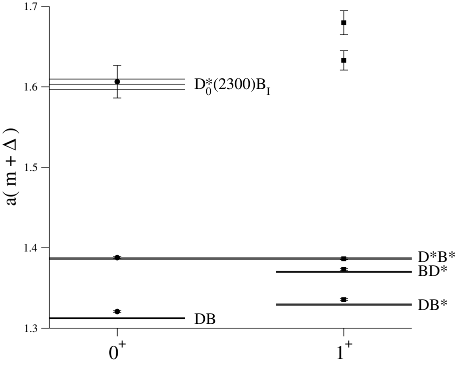

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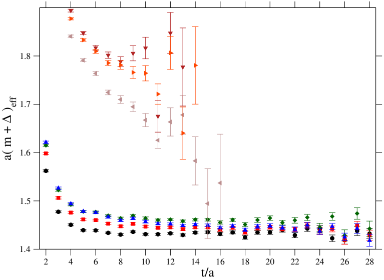

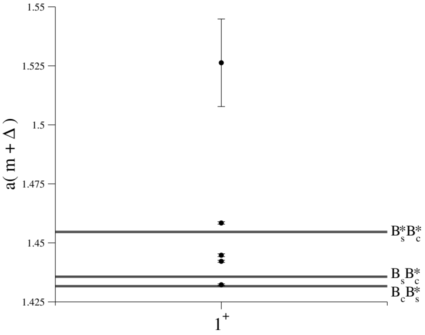

$sc\bar{b}\bar{b}$

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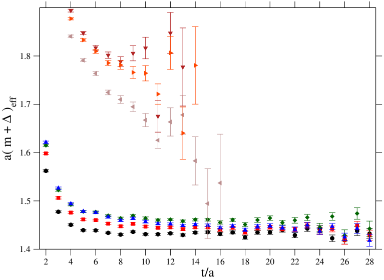

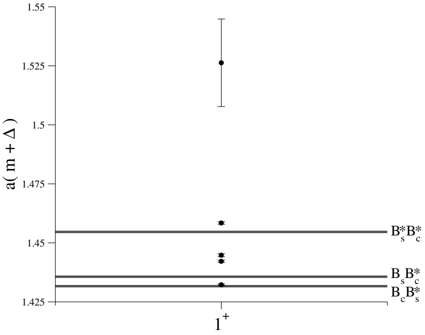

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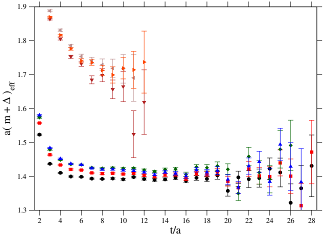

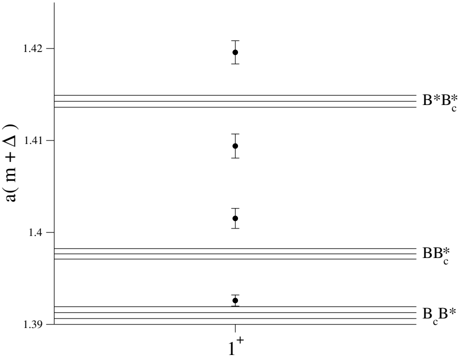

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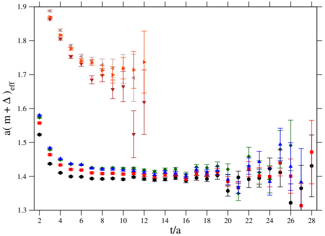

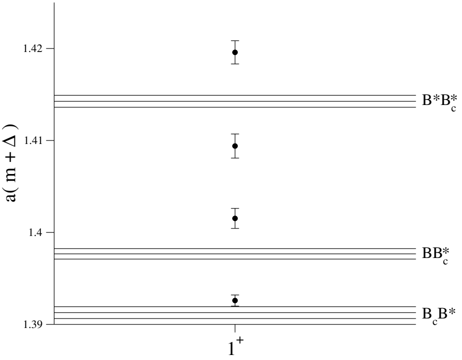

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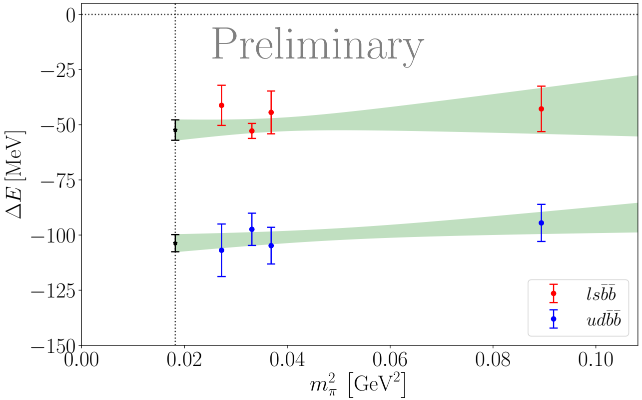
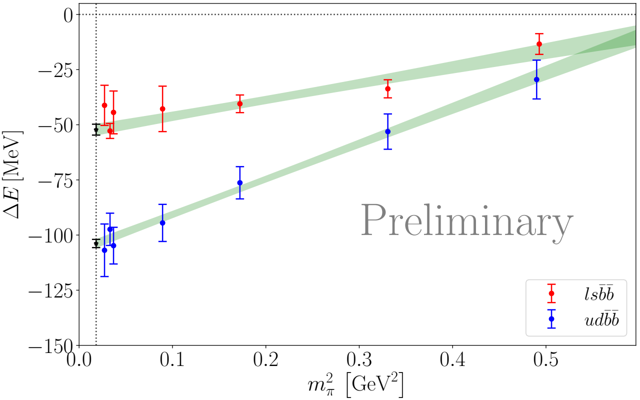
Doubly-bottom tetraquarks



- ★ $I = 0, J^P = 1^+ \; ud\bar{b}\bar{b}$ and $I = 1/2, J^P = 1^+ \; \ell s\bar{b}\bar{b}$ strong-interaction stable.
- ★ Consistent binding of $ud\bar{b}\bar{b}$ found by lattice groups + preliminary $\ell s\bar{b}\bar{b}$.

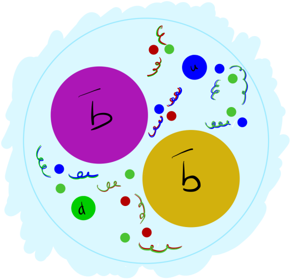
Doubly-bottom tetraquarks



- ★ $I = 0, J^P = 1^+$ $ud\bar{b}\bar{b}$ and $I = 1/2, J^P = 1^+$ $\ell s\bar{b}\bar{b}$ strong-interaction stable.
- ★ Consistent binding of $ud\bar{b}\bar{b}$ found by lattice groups + preliminary $\ell s\bar{b}\bar{b}$.

Summary

- ★ $I = 0,\ J^P = 1^+\ ud\bar{b}\bar{b}$ state consistently found stable on lattice: $\Delta E_{ud\bar{b}\bar{b}} \gtrsim 100\ \mathrm{MeV}$
- ★ Evidence for stable $I = 1/2,\ J^P = 1^+\ \ \ell s\bar{b}\bar{b}$: $\Delta E_{\ell s\bar{b}\bar{b}} \sim 50\ \mathrm{MeV}$
- ★ No evidence for deep binding in any other channel considered.
- ★ Chiral model deep binding predictions incompatible with lattice results; nonchiral colour magnetic spin-spin interaction models OK within current lattice errors.



Thank you!

Thank you

Extras

Operators

Type $(\psi\phi\theta\omega)$	$I(J)^P$	Diquark-Antidiquark	Dimeson
$udcb/udsb/udsc$	$0(1)^+$	$D(\gamma_5,\gamma_i), D(\gamma_t\gamma_5,\gamma_i\gamma_t)$ $E(\gamma_5,\gamma_i), E(\gamma_t\gamma_5,\gamma_i\gamma_t)$	$M(\gamma_5,\gamma_i)-N(\gamma_5,\gamma_i)$ $M(I,\gamma_i\gamma_5)-N(I,\gamma_i\gamma_5)$ $O(\gamma_5,\gamma_i)-P(\gamma_5,\gamma_i)$ $O(I,\gamma_i\gamma_5)-P(I,\gamma_i\gamma_5)$ $\epsilon_{ijk}M(\gamma_j,\gamma_k)$
	$0(0)^+$	$E(\gamma_5,\gamma_5), E(\gamma_t\gamma_5,\gamma_t\gamma_5)$	$M(\gamma_5,\gamma_5)-N(\gamma_5,\gamma_5)$ $M(I,I)-N(I,I)$ $M(\gamma_i,\gamma_i)$

Operators

Type $(\psi\phi\theta\omega)$	$I(J)^P$	Diquark-Antidiquark	Dimeson
$udbb$	$0(1)^+$	$D(\gamma_5,\gamma_i),\ D(\gamma_t\gamma_5,\gamma_i\gamma_t)$	$M(\gamma_5,\gamma_i)-N(\gamma_5,\gamma_i)$ $M(I,\gamma_i\gamma_5)-N(I,\gamma_i\gamma_5)$
$lsbb/ucbb/scbb$	$\frac{1}{2}(1)^+$	$D(\gamma_5,\gamma_i),\ D(\gamma_t\gamma_5,\gamma_i\gamma_t)$	$M(\gamma_5,\gamma_i),\ M(I,\gamma_i\gamma_5)$ $N(\gamma_5,\gamma_i),\ N(I,\gamma_i\gamma_5)$ $\epsilon_{ijk}M(\gamma_j,\gamma_k)$

Operators

Type ($\psi\phi\theta\omega$)	$I(J)^P$	Diquark-Antidiquark	Dimeson
$uscb$	$\frac{1}{2}(1)^+$	$D(\gamma_5, \gamma_i),\ D(\gamma_t\gamma_5, \gamma_i\gamma_t)$ $E(\gamma_5, \gamma_i),\ E(\gamma_t\gamma_5, \gamma_i\gamma_t)$	$M(\gamma_5, \gamma_i),\ M(I, \gamma_i\gamma_5)$ $N(\gamma_5, \gamma_i),\ N(I, \gamma_i\gamma_5)$ $O(\gamma_5, \gamma_i),\ O(I, \gamma_i\gamma_5)$ $\epsilon_{ijk}M(\gamma_j, \gamma_k)$
	$\frac{1}{2}(0)^+$	$E(\gamma_5, \gamma_5),\ E(\gamma_t\gamma_5, \gamma_t\gamma_5)$	$M(\gamma_5, \gamma_5),\ M(I, I)$ $N(\gamma_5, \gamma_5),\ N(I, I)$ $M(\gamma_i, \gamma_i)$

NRQCD tuning